

# High-power femtosecond pulses without a modelocked laser: supplementary material

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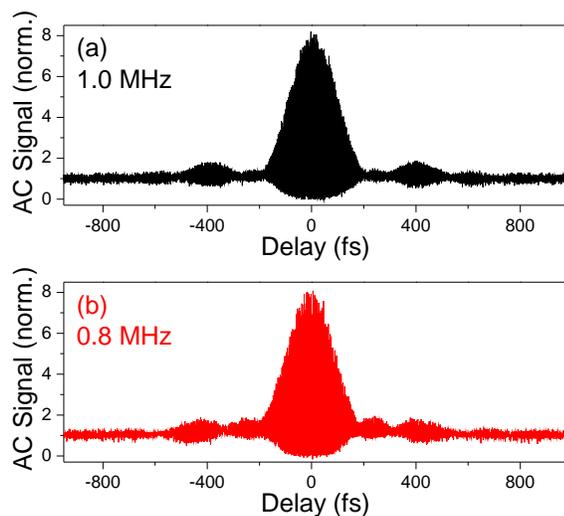
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## 1. REPETITION RATE FLEXIBILITY

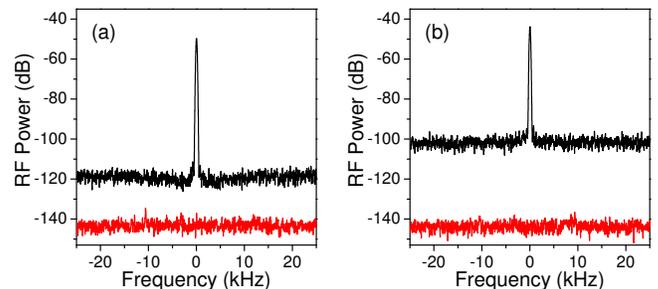
The gain-switched diode can be electronically triggered at arbitrary repetition rates. Provided the amplifiers are adjusted to maintain the same pulse energy in each stage, the nonlinear evolution remains unchanged, and the same level of performance can be maintained. By way of example, Figure S1 depicts the pulses obtained at 0.8 MHz. Slight differences with the 1 MHz results presented in the main text can be observed, most likely due to the amplifier powers being imperfectly adjusted. However, the main features remain unchanged: the pulse energy at 0.8 MHz is still 2.4- $\mu$ J, and the pulses still dechirp to 150 fs (roughly 10% longer than the transform limit).



**Fig. S1.** Comparison of the autocorrelations obtained at (a) 1.0 MHz and (b) 0.8 MHz.

## 2. NOISE CHARACTERIZATION

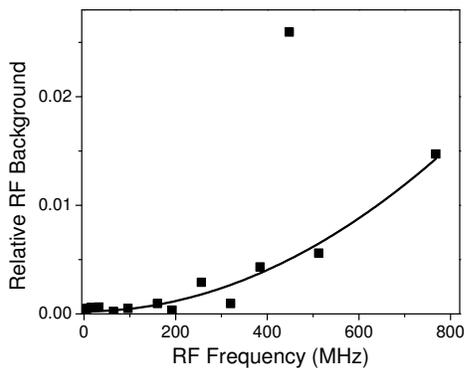
We quantitatively assess the pulse-to-pulse fluctuations using RF spectral intensity measurements. Figures S2(a) and S2(b) show the RF spectra observed using a one-photon detector and a two-photon detector, respectively, each measured at the 1-MHz fundamental with a resolution bandwidth of 200 Hz. In both cases, the spectra consist primarily of the expected comb line and a uniform background. Following the formalism presented in [1], we interpret the latter predominantly as uncorrelated, pulse-to-pulse amplitude noise, which is consistent with theoretical expectations for a gain-switched diode-based source [2]. The relative magnitude of this noise can be derived from the ratio between the peak of the comb line and the uniform background, and is 2% for the one-photon case (corresponding to energy jitter) and 6% for the two-photon case (corresponding to jitter in the two-photon photocurrent, which is proportional to the product of energy and peak power).



**Fig. S2.** Measured RF spectra at the system output using (a) a one-photon detector and (b) a two-photon detector. Both spectra are centered at 1 MHz, and have a resolution bandwidth of 200 Hz. Corresponding noise floors are shown in red.

We determine the timing jitter by measuring the RF spectra centered at harmonics of the repetition rate. As we look at higher

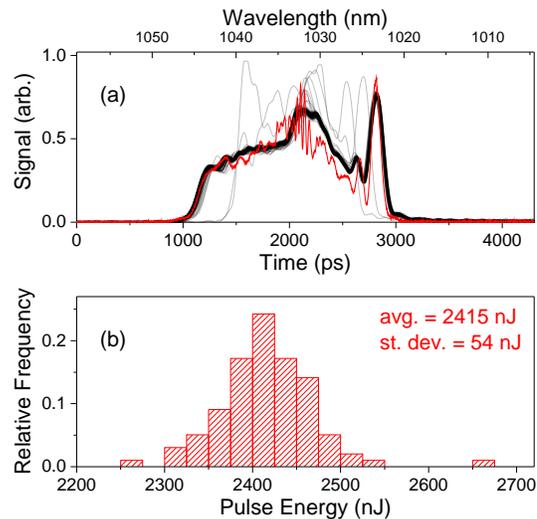
RF frequencies, the overall shape of the RF spectrum remains similar to that shown in Figure S2, but the relative background level gradually increases. This growth obeys a quadratic dependence that is a signature of pulse-to-pulse timing jitter (Fig. S3). The background near a given harmonic remains uniform, rather than forming a pedestal around the harmonic; we therefore interpret this as uncorrelated timing jitter, as opposed to the correlated variant observed in most modelocked systems. Keeping with the same formalism as before, we fit the relationship between the relative background and the RF frequency with a quadratic function, omitting a clear outlier at 448 MHz which we attribute to experimental error. Direct comparison between this fit and equation 3 in [1] (assuming negligible correlated pulse-to-pulse noise) lets us extract a timing jitter of  $40 \pm 20$  ps. We remark that this method for measuring timing jitter is equivalent to that used by [2] if amplitude jitter and correlated pulse-to-pulse noise are both negligible.



**Fig. S3.** Dependence of the RF spectrum background (relative to the comb tooth amplitude) on the RF frequency, measured here at several harmonics of the 1-MHz fundamental. The solid line represents a quadratic fit as described in the text, with the outlier at 448 MHz omitted.

As an additional sanity check, both the energy jitter and the timing jitter can be independently estimated from dispersive Fourier transform measurements [3]. We disperse the pulses in roughly 5.5 km of standard, step-index fiber (SMF28). Because this fiber is not strictly single-mode at 1030 nm, a segment of single-mode fiber (Hi1060) is spliced to the end to filter out higher-order modes. We then directly measure the resulting pulse train with a fast photodetector and a 25-GHz oscilloscope with a long record length. A single sweep of the oscilloscope is used to measure a series of 100 consecutive pulses while preserving the true timing jitter. The pulses are overlaid using the nominal repetition rate in Figure S4, where it is evident that only two of the 100 pulses differ markedly from the average in their spectral shape. These two outliers do not noticeably skew the average spectrum (as measured by an optical spectrum analyzer; red line in Fig. S4a), nor do they correspond to extreme energies in the single-pulse energy distribution (Fig. S4b). Computing the time-integrated photodetector signal and the center-of-mass arrival time for each pulse, we find standard deviations of 2% and 30 ps, respectively, in reasonable agreement with the energy jitter and timing jitter derived from RF spectral analysis.

It is important to note that this kind of timing jitter derives from a fundamentally different cause than the kind typically seen in modelocked oscillators. In the case of the latter, the jitter is correlated from one roundtrip to the next, causing the



**Fig. S4.** (a) Dispersive Fourier transform spectral measurements for 100 consecutive pulses. Red: average spectrum measured with an optical spectrum analyzer, for comparison. (b) Histogram of corresponding pulse energies.

pulse's arrival time to drift gradually and continuously over time. Over sufficiently short observation periods, the accumulated timing jitter is negligible. Over longer observation periods, however, if active stabilization techniques are not used, the timing jitter can reach picosecond scales [4, 5]. Timing jitter in modelocked oscillators therefore depends on the observation period (or, equivalently, on the range of RF frequencies over which the noise is integrated). By contrast, timing jitter in a gain-switched diode is uncorrelated from pulse to pulse. Each new pulse forms from spontaneous emission noise, and so the arrival times of any two pulses are independent of one another. Following from the statistics of the initial noise, the arrival times do nonetheless have a statistical distribution. The measured timing jitter represents the width of this distribution, and is independent of the observation time. A comparison of timing jitter in modelocked oscillators and gain-switched diodes is therefore meaningless without specifying an observation period (i.e., a frequency range). Over a short observation time, a gain-switched diode will exhibit greater jitter than an oscillator; over a sufficiently long time, an unstabilized oscillator will undergo an unbounded random walk, while a gain-switched diode will remain anchored within some smaller range of its external trigger [6]. Timing jitter characterization based on a single number obfuscates this difference, and can be misleading.

There certainly exist applications for which a 40-ps uncertainty in the arrival time of a 150-fs pulse will be problematic. These applications are those that require carrier-envelope offset stabilization (i.e., most frequency comb applications), those that require synchronization of the pulsed source to some other device with sub-40-ps precision, and those that require interactions between subsequent pulses in a pulse train. In such cases, oscillators using active timing stabilization are typically used to achieve timing jitter on the femtosecond or even attosecond level over typical frequency ranges [7, 8]. Nevertheless, the majority of mature applications are insensitive to our observed timing jitter, including many of the most popular applications of high-power, ultrafast fiber lasers. Numerous systems only require synchronization to scanning optics on nanosecond or microsec-

ond time scales. This is the case in most types of machining and multiphoton microscopy, where there is only one beam present and pulses need only fall within a given dwell time. Still other applications use a single, master oscillator, and derive multiple pulse trains from a beam splitter (e.g., multi-wavelength sources or optical parametric amplifiers, as well as standard pump-probe experiments). In these instances, recombination of the same pulse later in the system can render inter-pulse timing jitter a non-issue.

### 3. ADDITIONAL TECHNICAL DETAILS

Our Mamyshev regenerator filter takes the form of a 1000 l/mm diffraction grating and a fiber-pigtailed collimator. Together, these effect a tunable, Gaussian bandpass filter with a full-width-half-max of 0.65 nm. Both the preamplifier and the main amplifier in our system are pumped at 976 nm. In the results we present, we pump the main amplifier with up to 19 W in the counterpropagating configuration, using free-space coupling for experimental expediency. Pulse compression is performed using a pair of 1000 l/mm diffraction gratings, which compensate 0.34 ps<sup>2</sup> of group delay dispersion. Simulations suggest that third-order dispersion from the compressor does not significantly degrade the dechirped pulse quality.

Dispersive Fourier transform measurements are performed by dispersing the pulses in roughly 5.5 km of standard, step-index fiber (SMF28). Because this fiber is not strictly single-mode at 1030 nm, a segment of single-mode fiber (Hi1060) is spliced to the end to filter out higher-order modes. The resulting pulse train is then directly measured with a fast photodetector and a 25-GHz oscilloscope with a long record length. A single sweep of the oscilloscope is used to measure a series of 100 consecutive pulses while preserving the true timing jitter.

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